Blade Boundary Layer Resolved Computations of the NREL 5MW Rotor in a Realistic Atmospheric Boundary Layer using Hybrid URANS-LES

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2nd Symposium on OpenFOAM in Wind Energy

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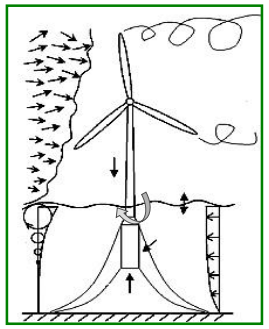
- Penn State: Institutes of Energy and the Environment, CyberScience Institute, Aerospace and Mechanical Engineering
- Computer Resources: NSF XSEDE program; DOE Oak Ridge National Laboratory

Penn State Cyber Wind Facility Program



MESOSCALE, WEATHER

*ATMOSPHERIC BOUNDARY LAYER TURBULENT WINDS

WAKE TURBULENCE BLADE-WAKE-ATMOSPHERE

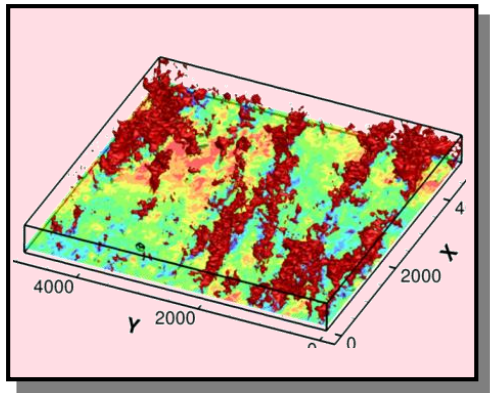
*PLATFORM-WAVE HYDRODYNAMICS and 6-DOF MOTIONS

*BLADE AERODYNAMICS, SPACE-TIME LOADINGS (Hybrid URANS/LES)

WAKE-TURBINE INTERACTIONS (wind plant)

*BLADE AND *TOWER ELASTIC DEFORMATION

*Shaft Torque, *Drivetrain Loadings



CYBER WIND FACILITY

- **highly resolved 4-D cyber data**
- **coupled atmospheric turbulence-blade loadings-shaft torque data**
- coupled wave structure – platform motion – turbine loadings data
- experiment design, test-bed, turbine design, controls concepts and testing

*sensors, controllers, diagnostics

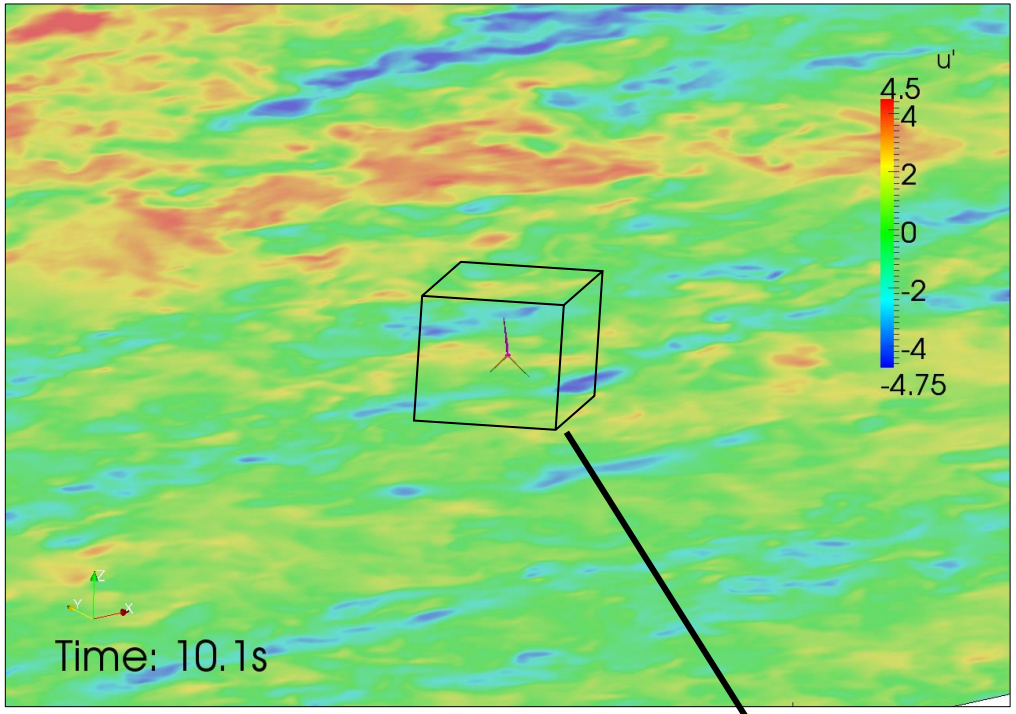
Motivation and objective

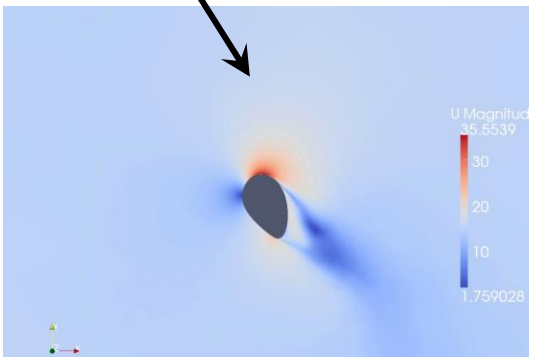
Wind turbines fail sooner than expected

- **Gearboxes, blades, shafts, …**

Atmospheric Boundary Layer (ABL)

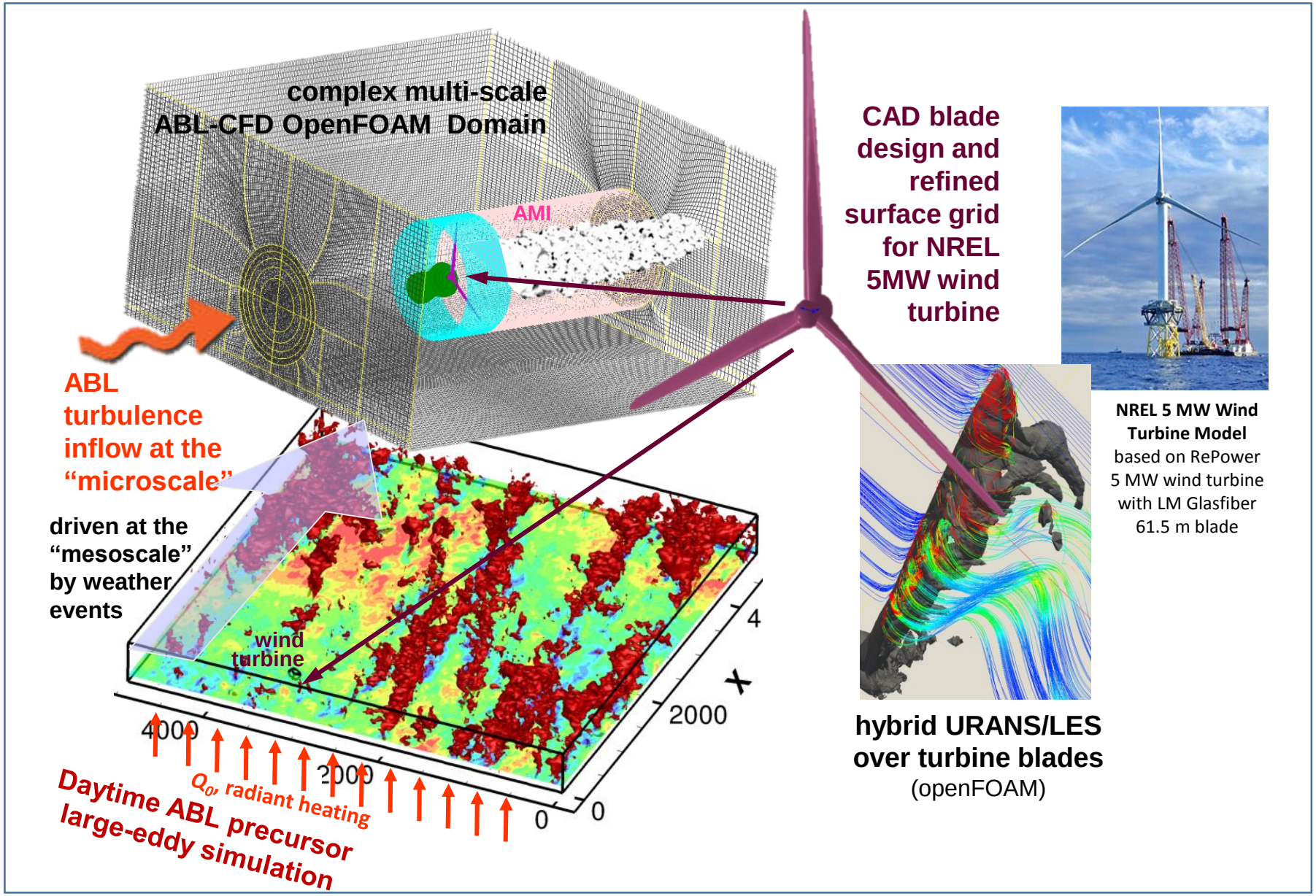
- **Size of most energetic turbulence structures ~ wind turbine disk**





Study the response of blade boundary layer to forcing by Atmospheric Turbulence

The Current Cyber Wind Facility

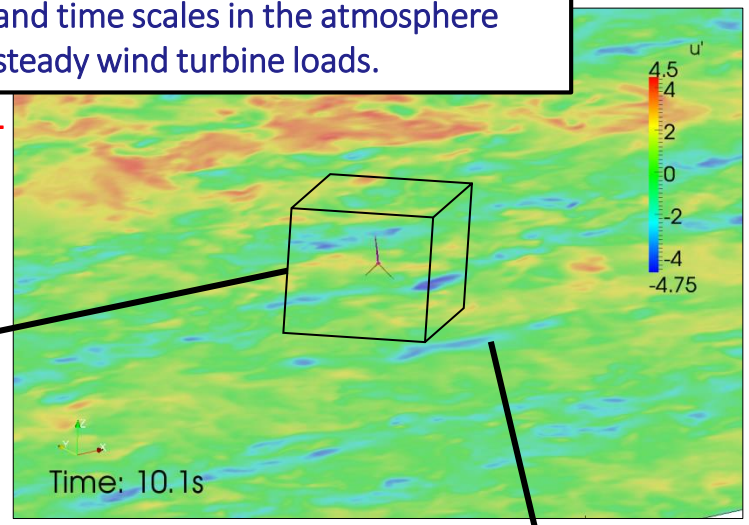


Outline

Study the response of blade boundary layer to forcing by Atmospheric Turbulence

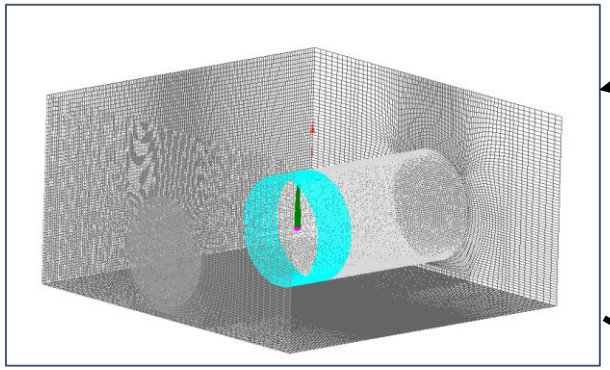
1. Quantify length and time scales in the atmosphere relevant to non-steady wind turbine loads.

PHYSICS OF ABL



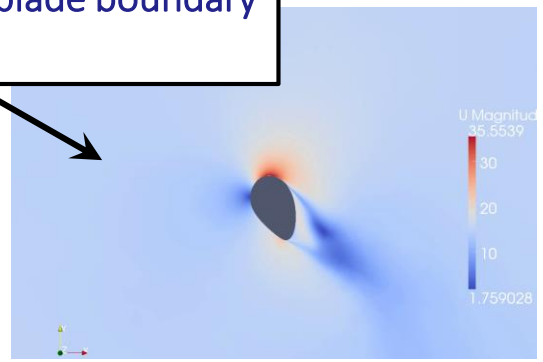
NUMERICAL METHODS

2. Propagation of ABL turbulence into wind turbine OpenFOAM ABL-CFD domain

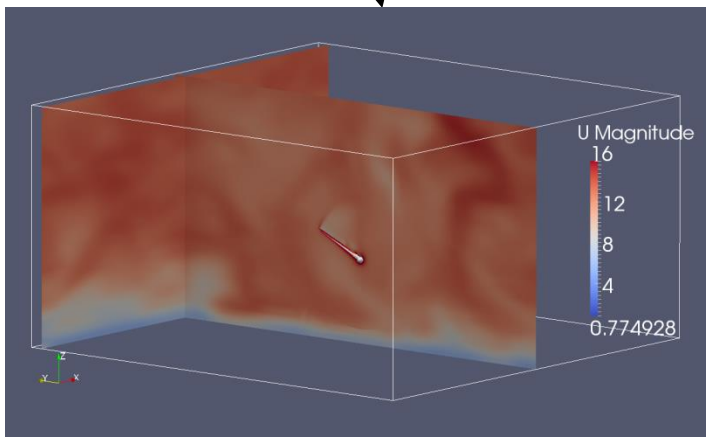


3. Interface ABL with blade boundary layer dynamics

NUMERICAL METHODS

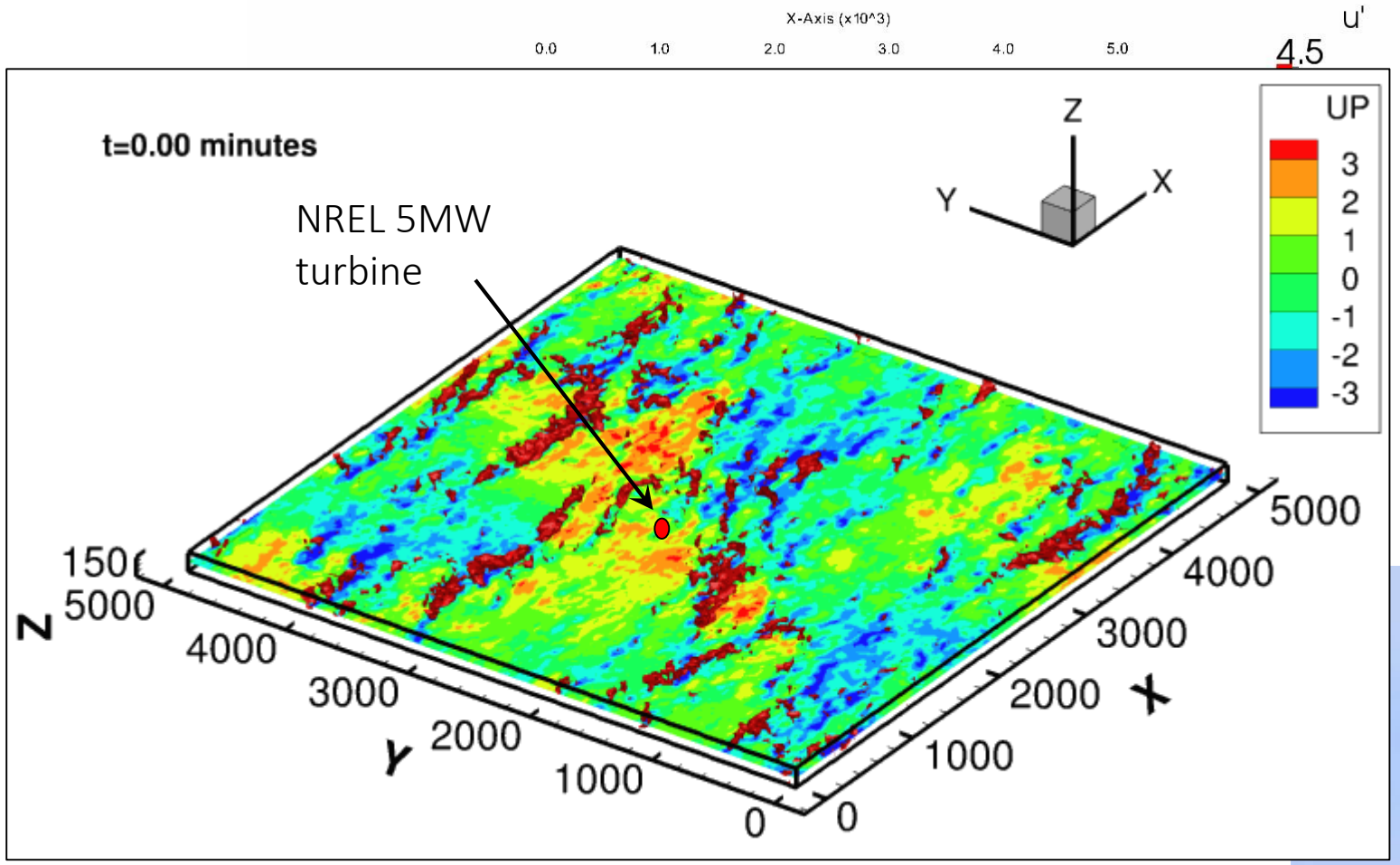


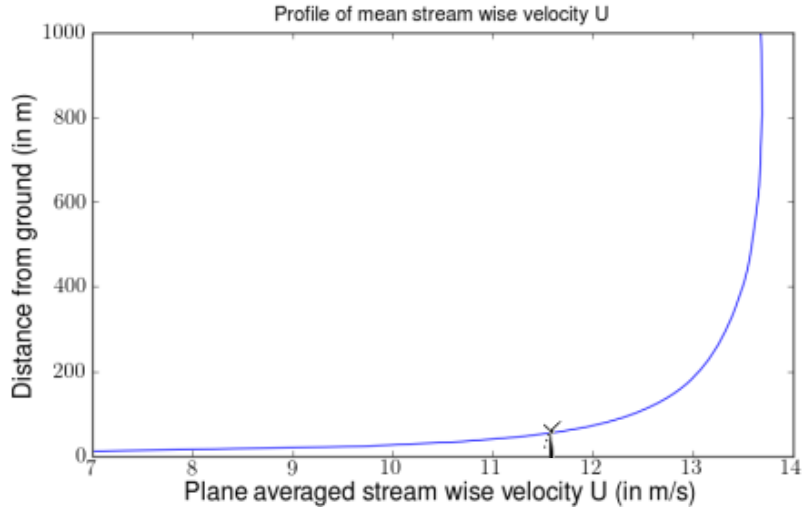
4. Results

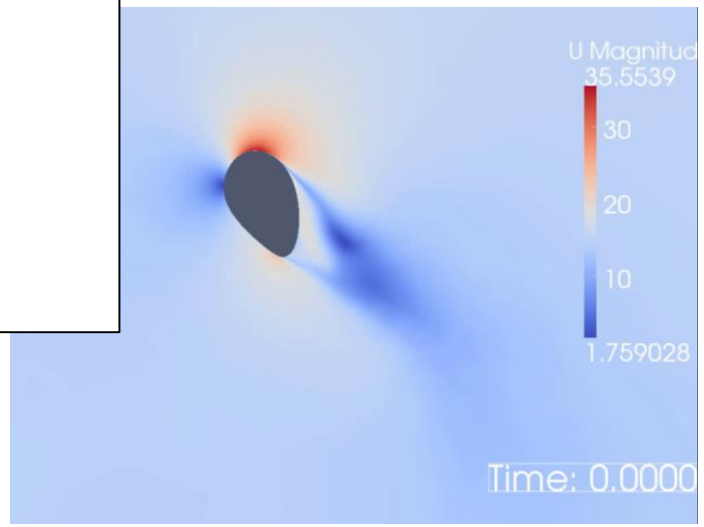


Turbulence structure in the Atmospheric Surface Layer

Moderately Convective Boundary Layer

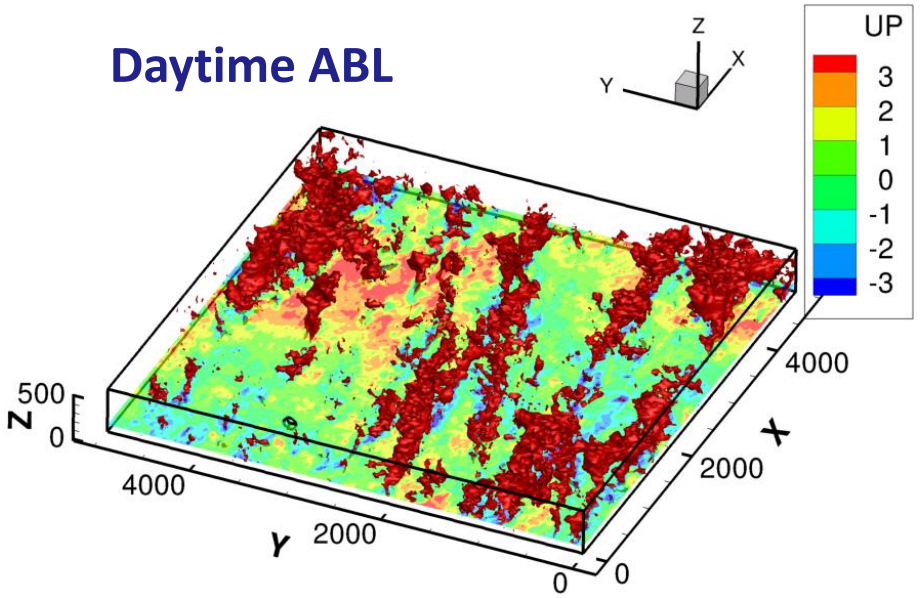






Atmospheric Boundary Layer - LES

Daytime ABL



ABL – Code

- Pseudo-spectral low dissipation
- Highly parallel –
  Sullivan and Patton (2008)
- Domain – 5km x 5km x 2km
- Grid – 512 x 512 x 256
- 14 m/s - Mean velocity @ Hub Height – Region III

Mesoscale – weather

$$\sim 10 - 100\ km$$

→

ABL - Eddies $\sim 100\ m$

→

Blade boundary layer $\sim 1\ mm$

→

Blade viscous sublayer $\sim 50\ \mu m$

Outline

Study the response of blade boundary layer to forcing by Atmospheric Turbulence

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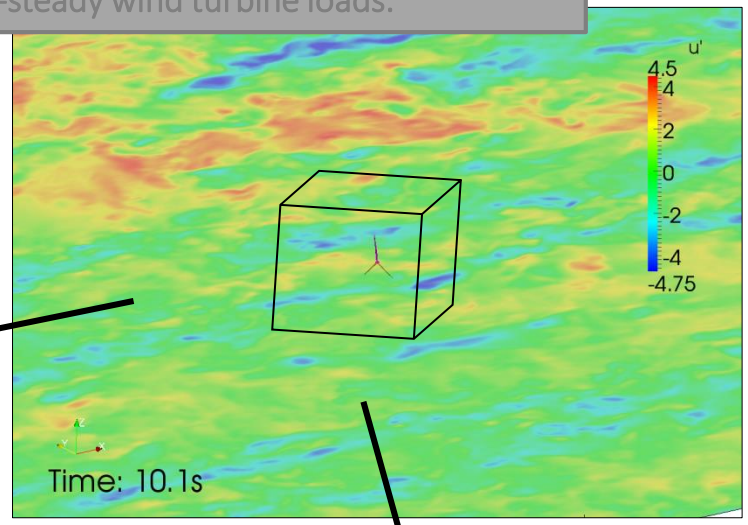
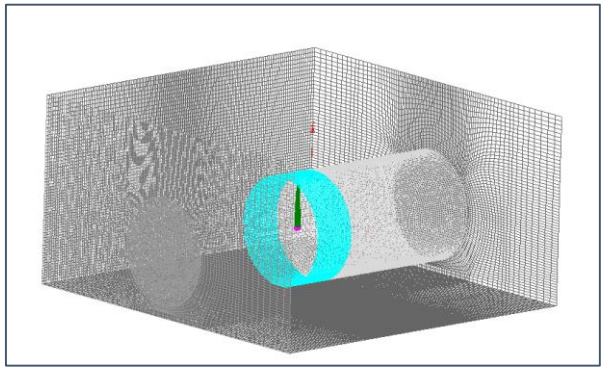


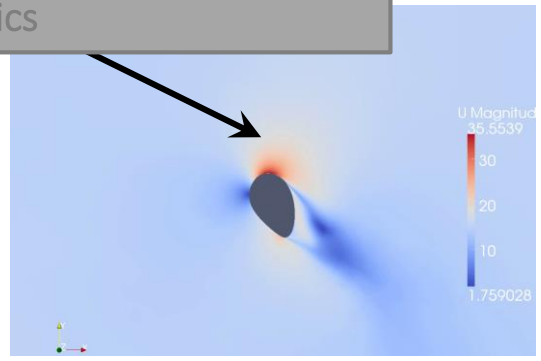
2 Propagation of ABL turbulence into wind turbine OpenFOAM ABL-CFD domain

NUMERICAL METHODS



3 Interface ABL with blade boundary layer dynamics

NUMERICAL METHODS



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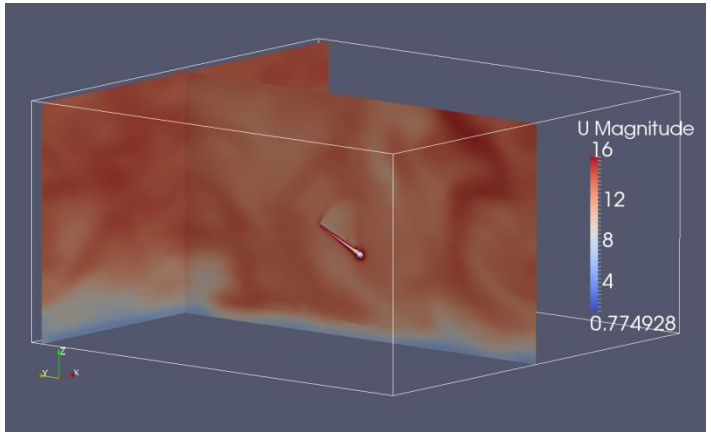
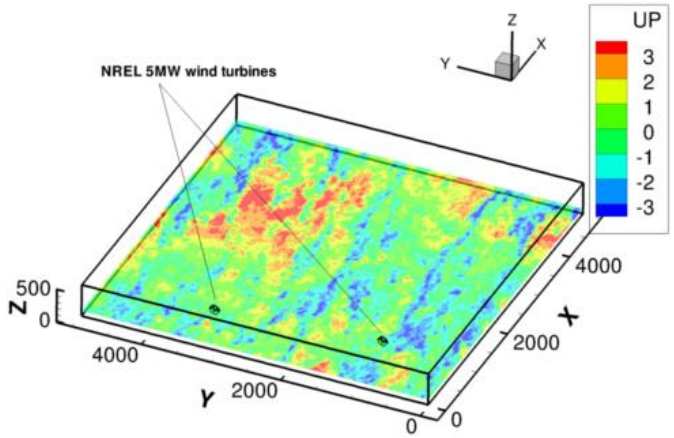
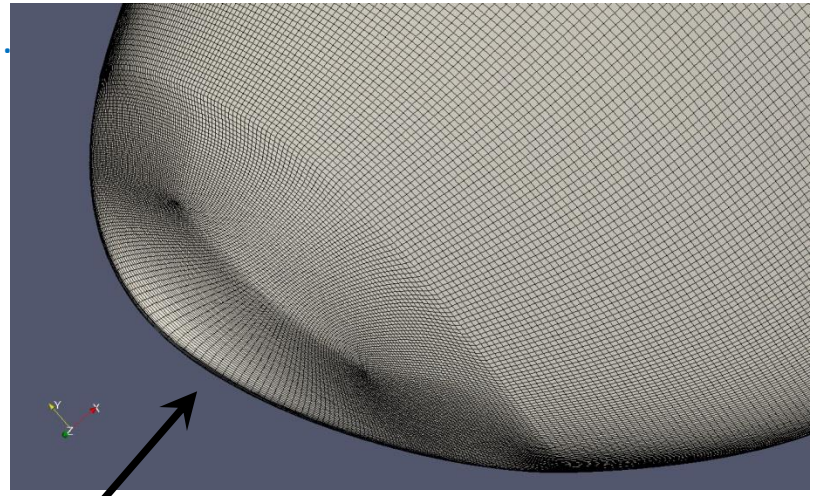


Design of Wind Turbine Geometry and Grid

Diameter – 126m, Rated power - 5MW @ 11.4 m/s and 12.



Blade $Re \sim 10^7$



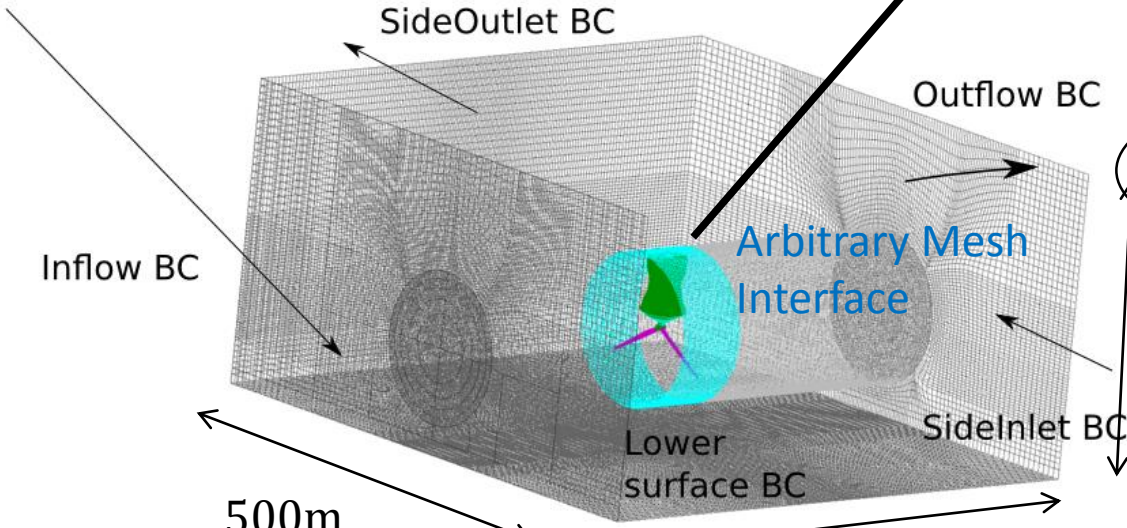
Designed to capture blade boundary layer separation dynamics

58 Million cells

~ 50 million near blade

9 Million cells

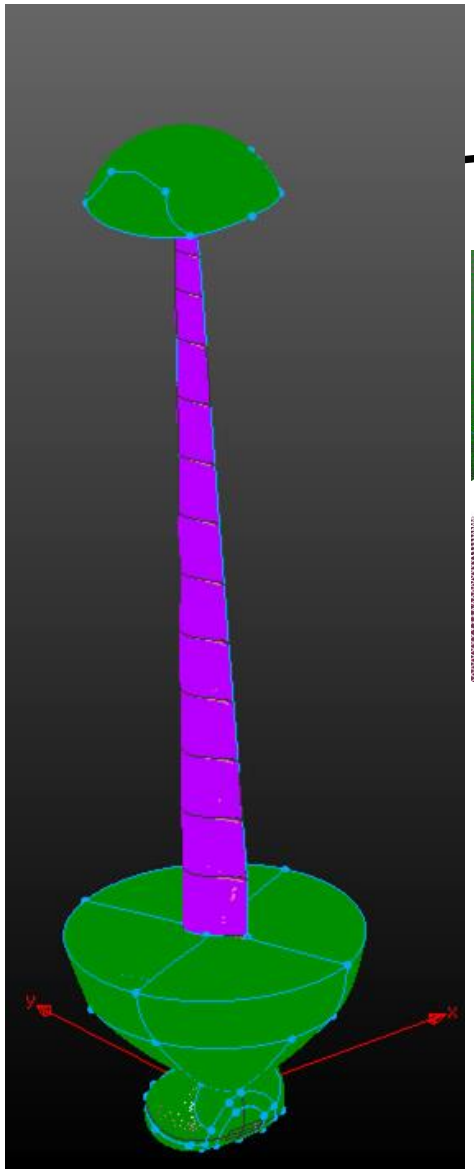
~ 5.5 million near blade

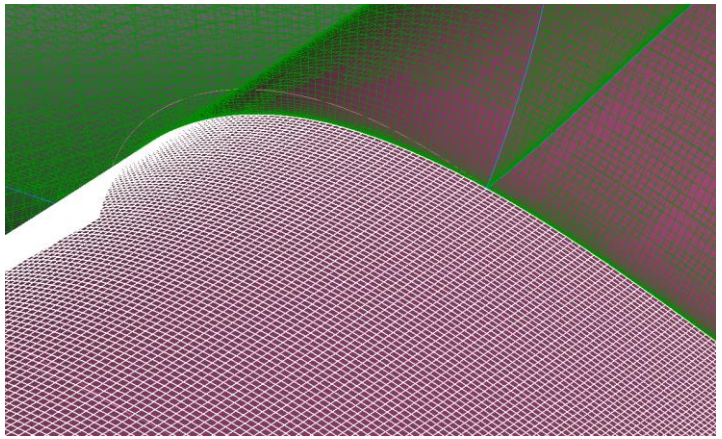


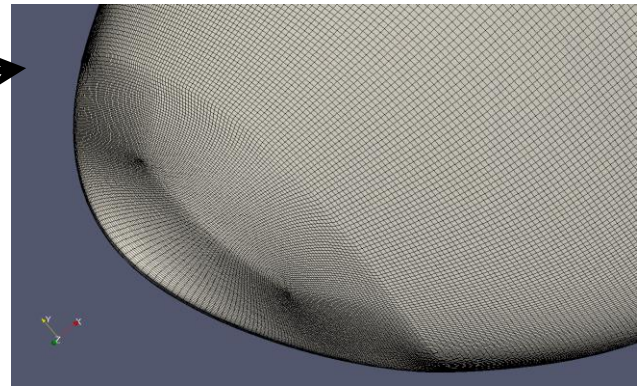
Complex rotor fitted grid – rotating mesh

OpenFOAM

Design of Wind Turbine Geometry and Grid







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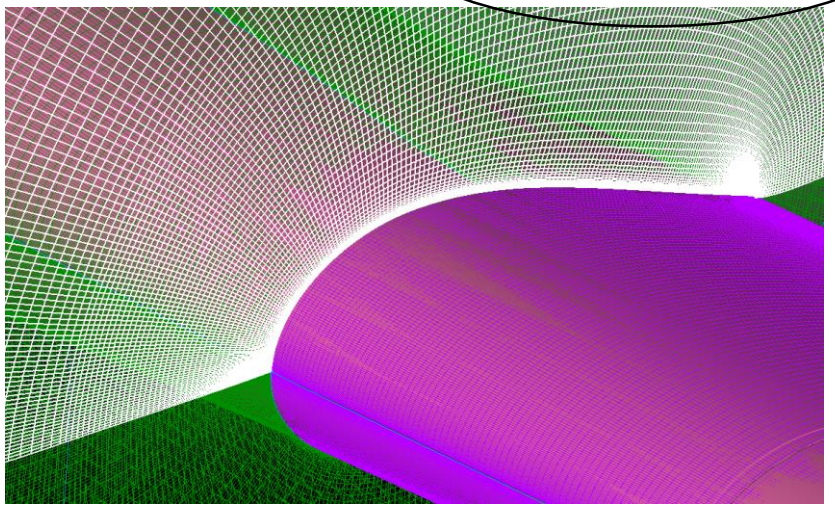
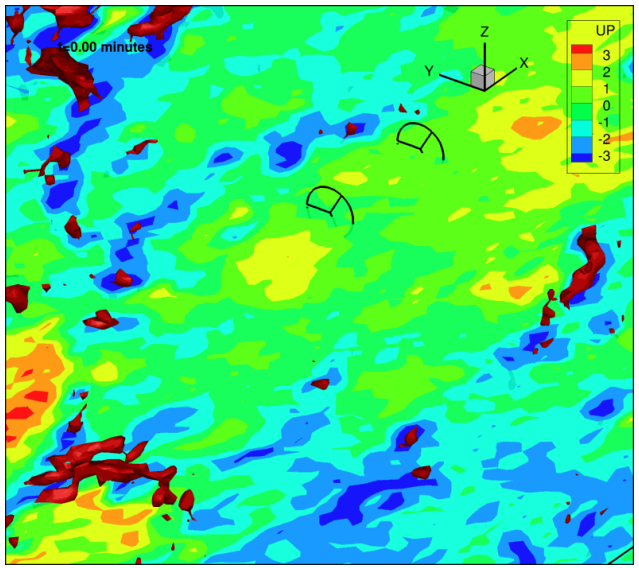


Coupling LES of ABL to CFD around wind turbine



2010-2011
Collaboration with Dr. Churchfield and Dr. Moriarty

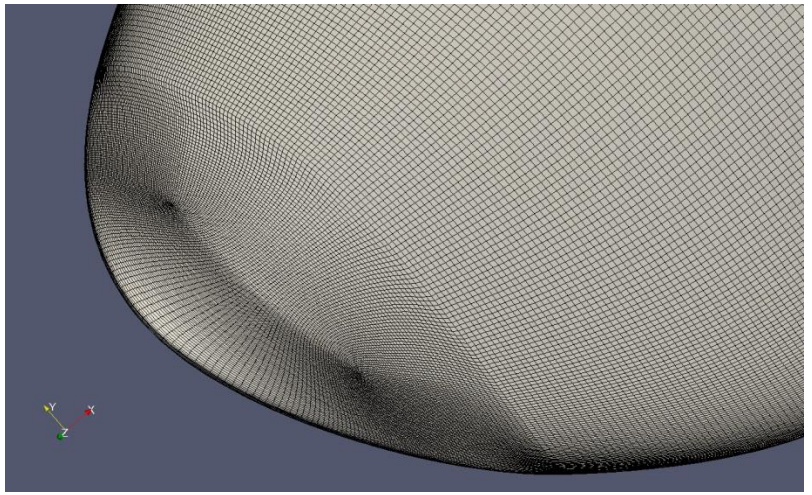
Extend spectral LES of ABL algorithm to finite volume method

$$Momentum: \quad \frac{\partial U_i}{\partial t} + \frac{\partial U_i U_j}{\partial x_j} = -\frac{1}{\rho_0}\left\langle \frac{\partial P}{\partial x_i} \right\rangle - \frac{1}{\rho_0}\frac{\partial P^*}{\partial x_i} - 2\Omega_i U_j \epsilon_{ijk} - g\frac{(\Theta - \langle\Theta\rangle)}{\Theta_0} - \frac{\partial \tau_{ij}}{\partial x_j}$$

Coriolis

Buoyancy - Boussinesq

Vijayakumar et. al.
AIAA 2012-0817



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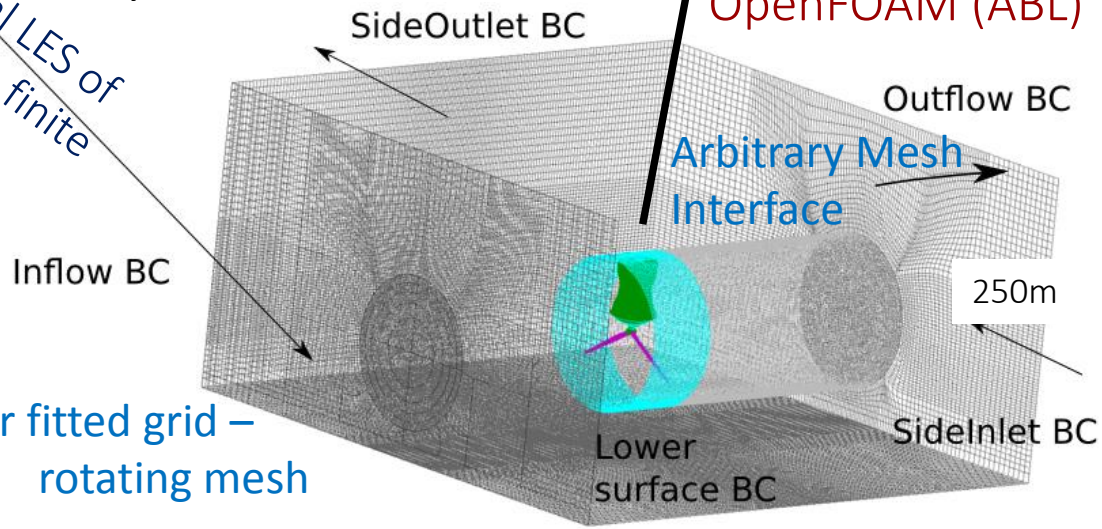
Blade $Re \sim 10^7$

OpenFOAM (ABL)



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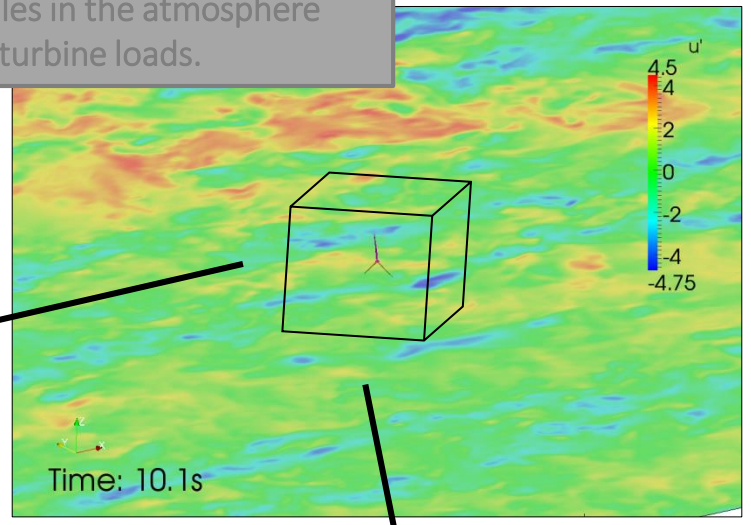

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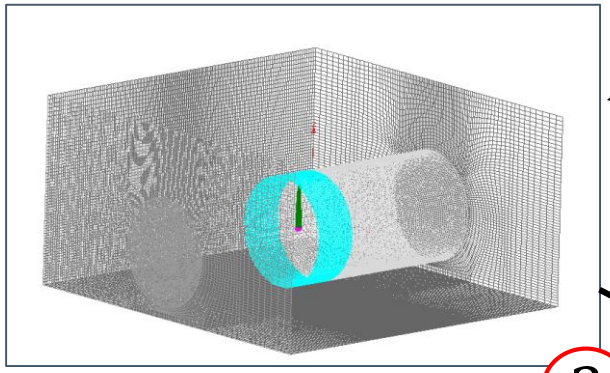
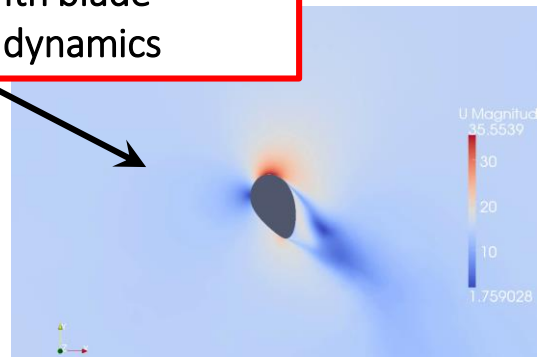
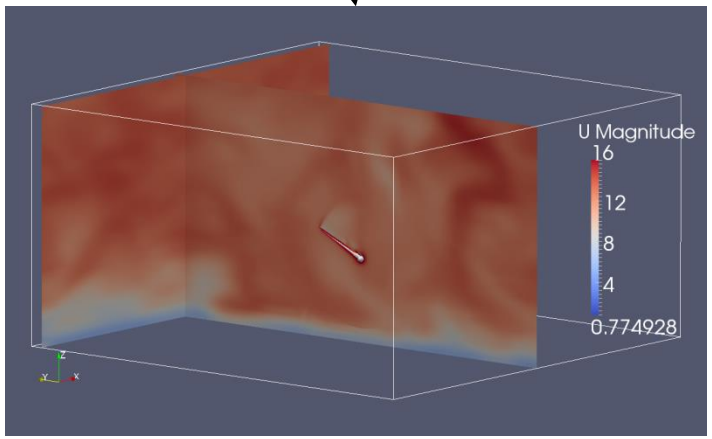


3 Interface ABL with blade boundary layer dynamics

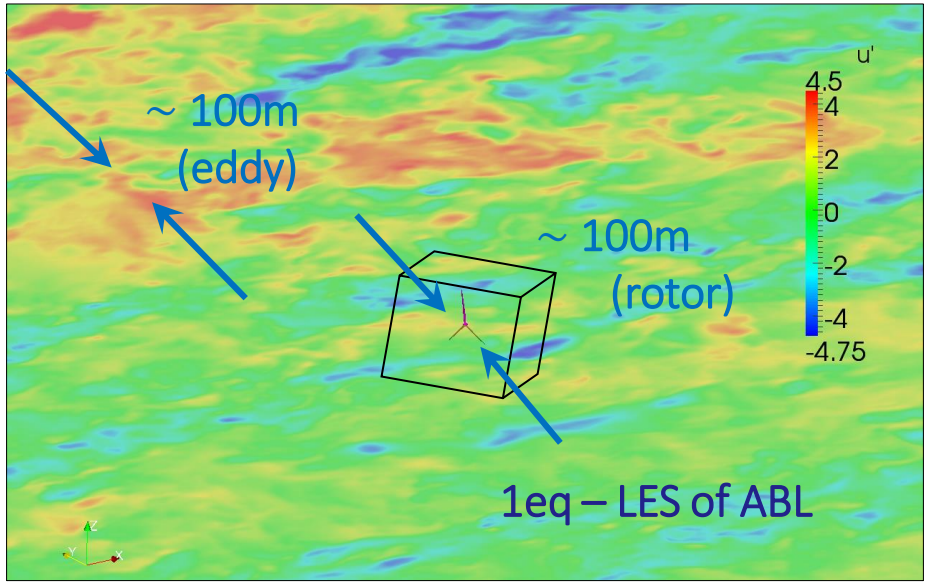
NUMERICAL METHODS

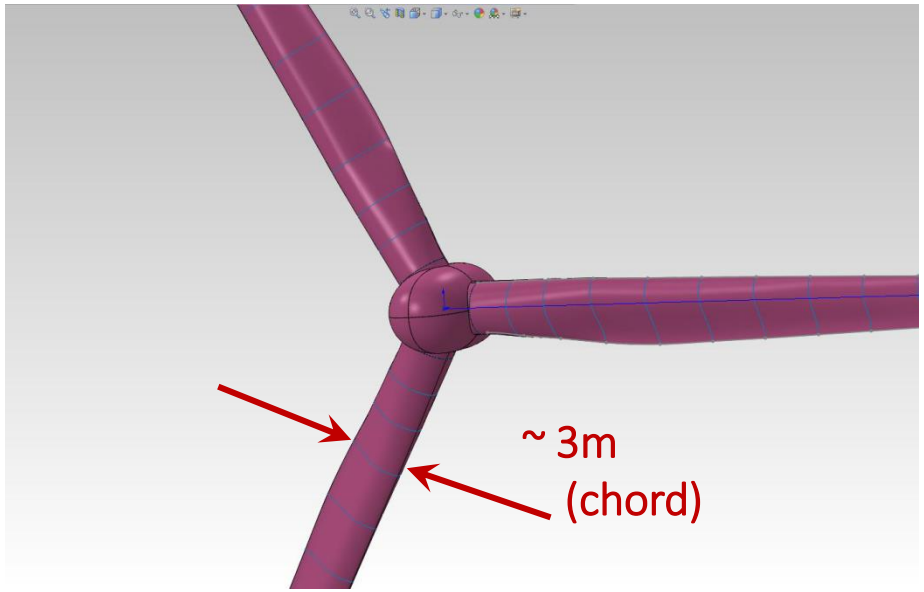


4 Results



Modeling range of length scales – ABL to Blade boundary layer





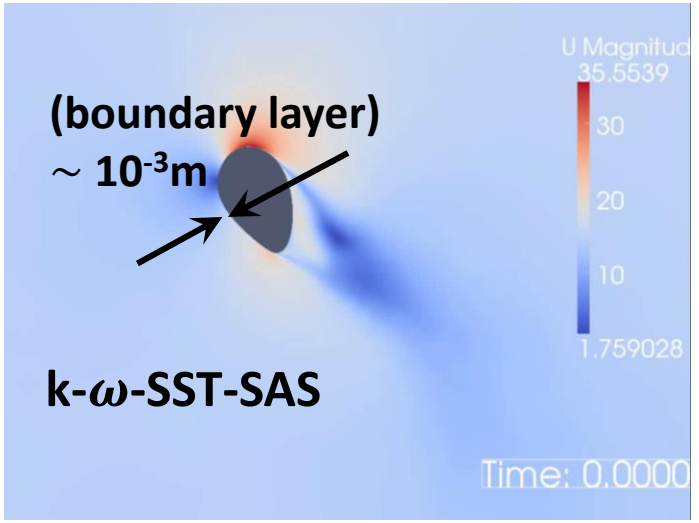
Mesoscale – weather $\sim 10 - 100km$

Rotor - ABL Turbulence $\sim 100m$

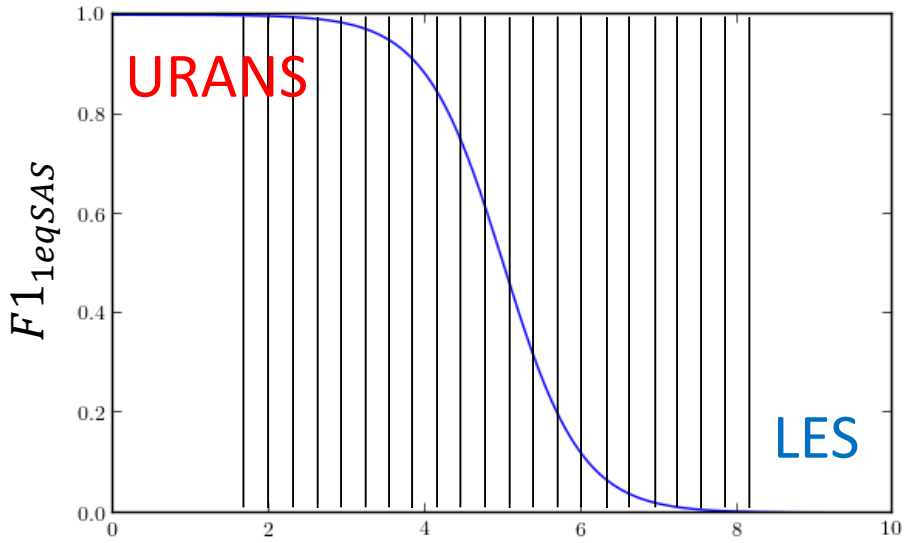
Blade chord $\sim 1m$

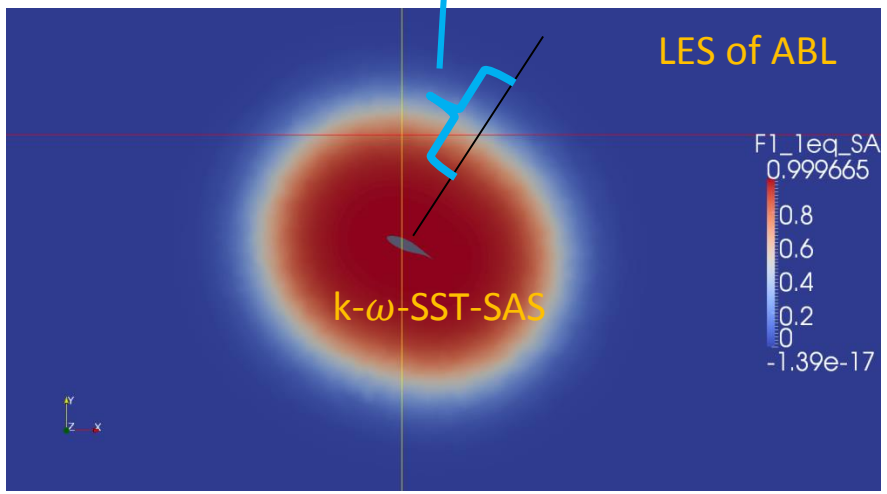
Blade boundary layer $\sim 1mm$

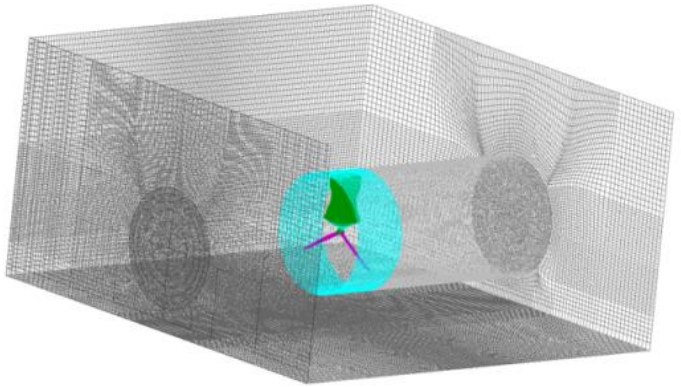
Blade viscous sublayer $\sim 50\mu m$



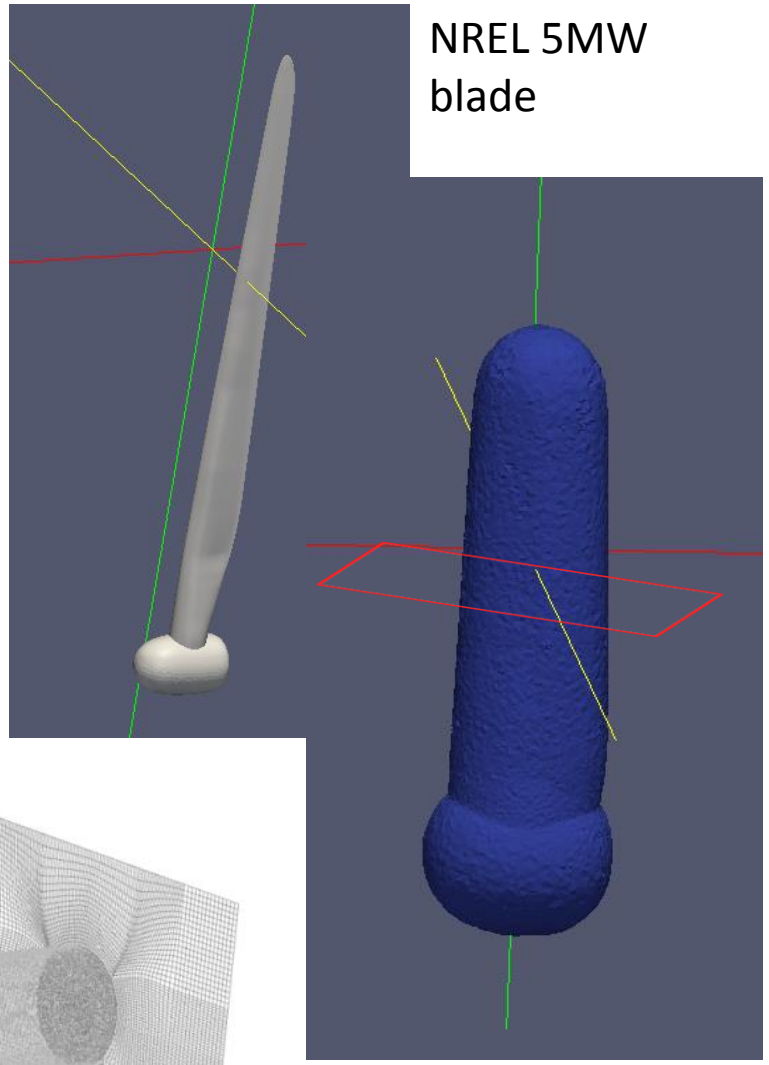
New method to blend LES of ABL with Hybrid URANS/LES near blade







NREL 5MW blade



Iso-surface of $F1_{1eqSAS} = 0.5$

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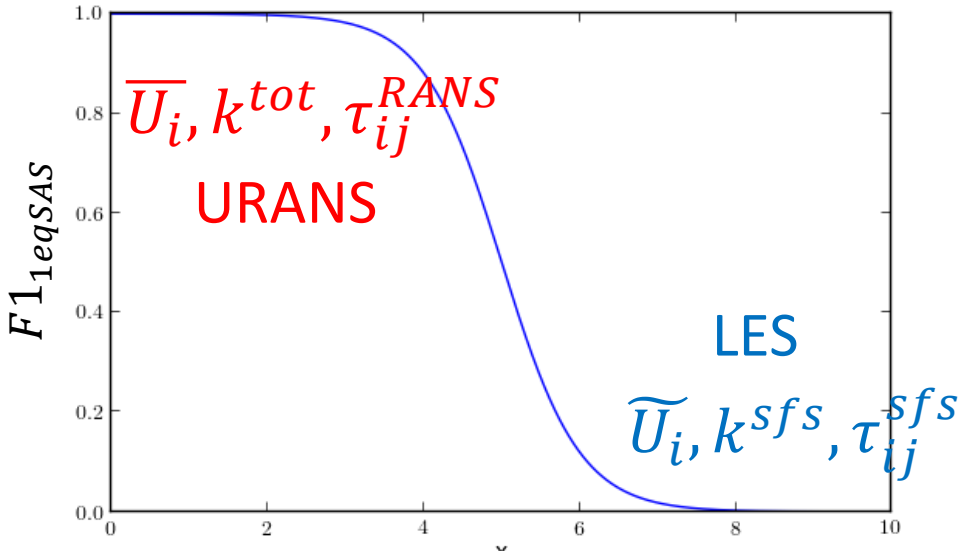
$$Momentum: \frac{\partial U_i}{\partial t} + \frac{\partial U_i U_j}{\partial x_j} = -\frac{1}{\rho_0}\left\langle\frac{\partial P}{\partial x_i}\right\rangle - \frac{1}{\rho_0}\frac{\partial P^*}{\partial x_i} - 2\Omega_i U_j \epsilon_{ijk} - g\frac{(\Theta - \langle\Theta\rangle)}{\Theta_0} - \frac{\partial \tau_{ij}}{\partial x_j}$$



$$\tau_{ij} = 2\,\nu\,S_{ij}$$
$$\nu = c\,l^*u^*$$

URANS

$l^* \sim \frac{\sqrt{k^{tot}}}{\omega}$ Integral scales

$u^* \sim \sqrt{k^{tot}}$

LES

$l^* \sim \Delta_f$ Filter scales

$u^* \sim \sqrt{k^{sfs}}$

$$\frac{\partial k}{\partial t} + U_j\frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\sigma_k\frac{\partial k}{\partial x_j}\right) + 2\nu_t S_{ij}S_{ij} - \frac{k^{\frac{3}{2}}}{l_{destruct}}$$

Advection | Diffusion | Production | Dissipation term

$l_{destruct}$:

URANS: $\frac{\sqrt{k}}{\beta\omega}$

LES: $\frac{\Delta_f}{C}$

OpenFOAM turbulence model class

Vijayakumar et. al.
AIAA 2014-0867

Recap

Study the response of blade boundary layer to forcing by Atmospheric Turbulence

1 Quantify length and time scales in the atmosphere relevant to non-steady wind turbine loads.

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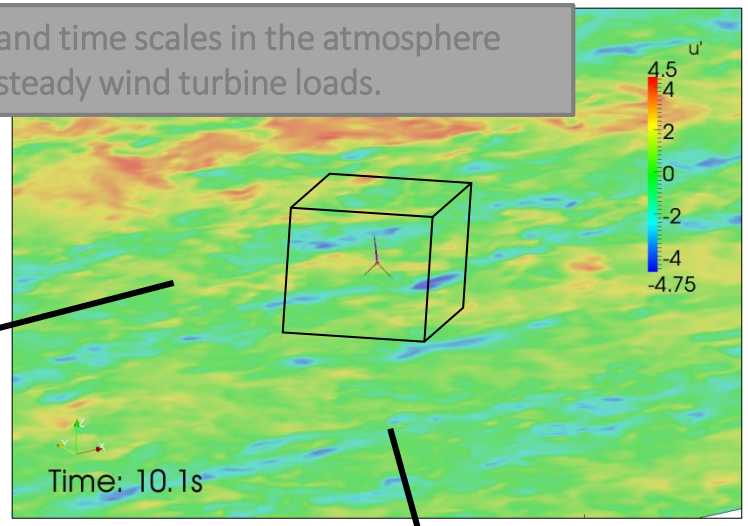

NUMERICAL METHODS

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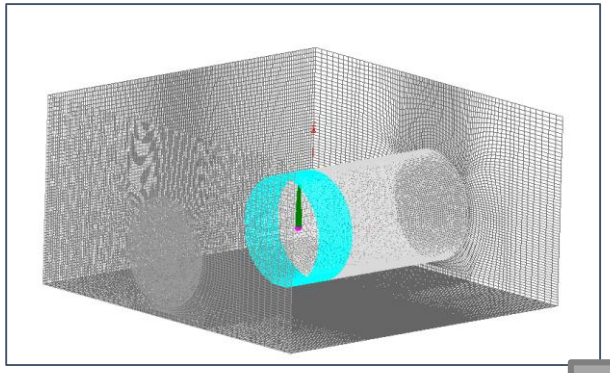

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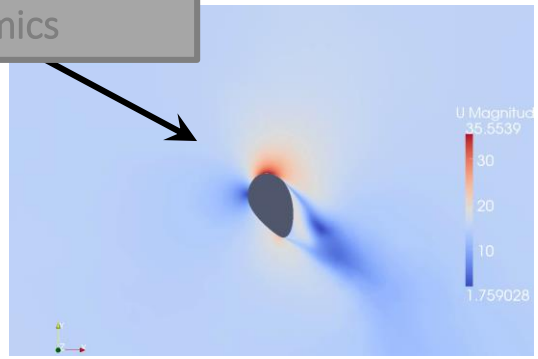
NUMERICAL METHODS



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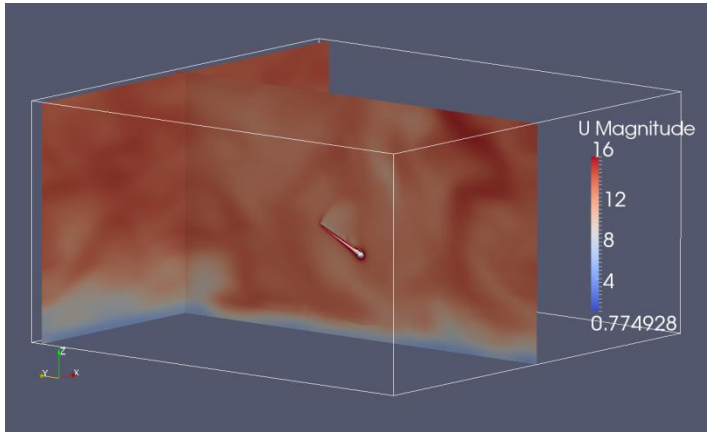
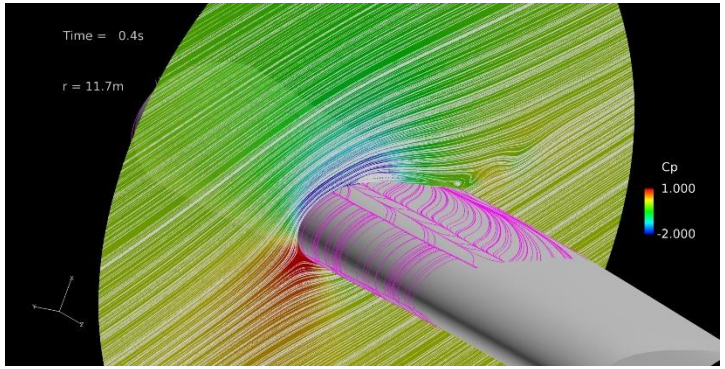
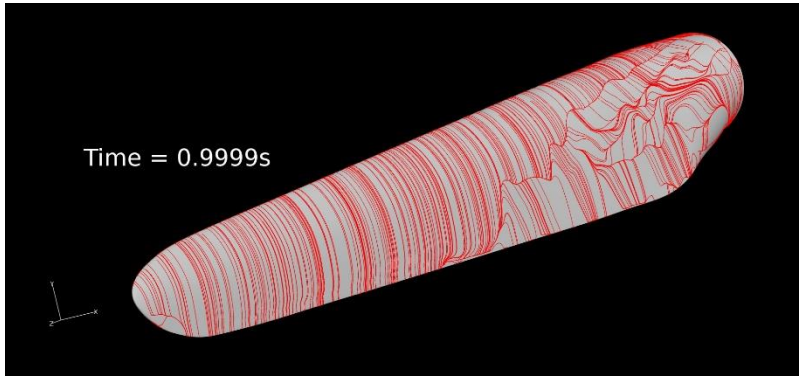


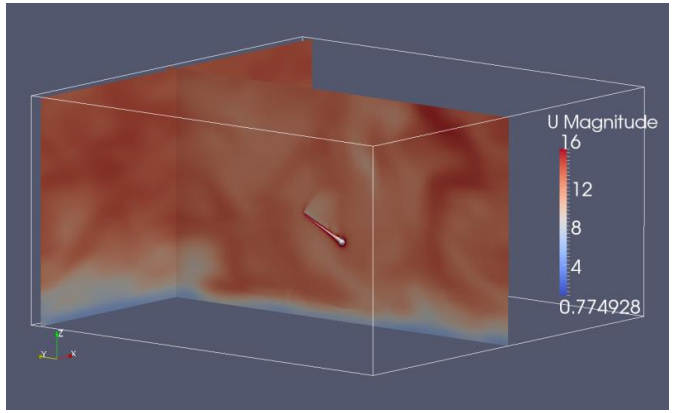
OpenFOAM tools for data analysis

Sampling on cut planes rotating with the inner domain

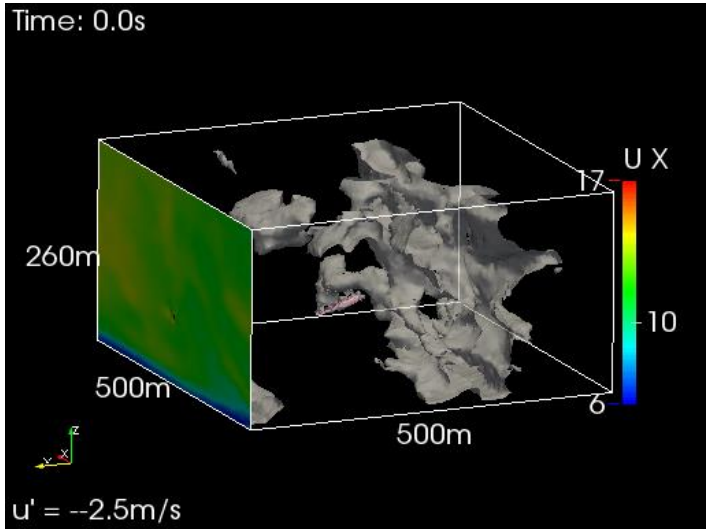


Blade surface data without interpolation

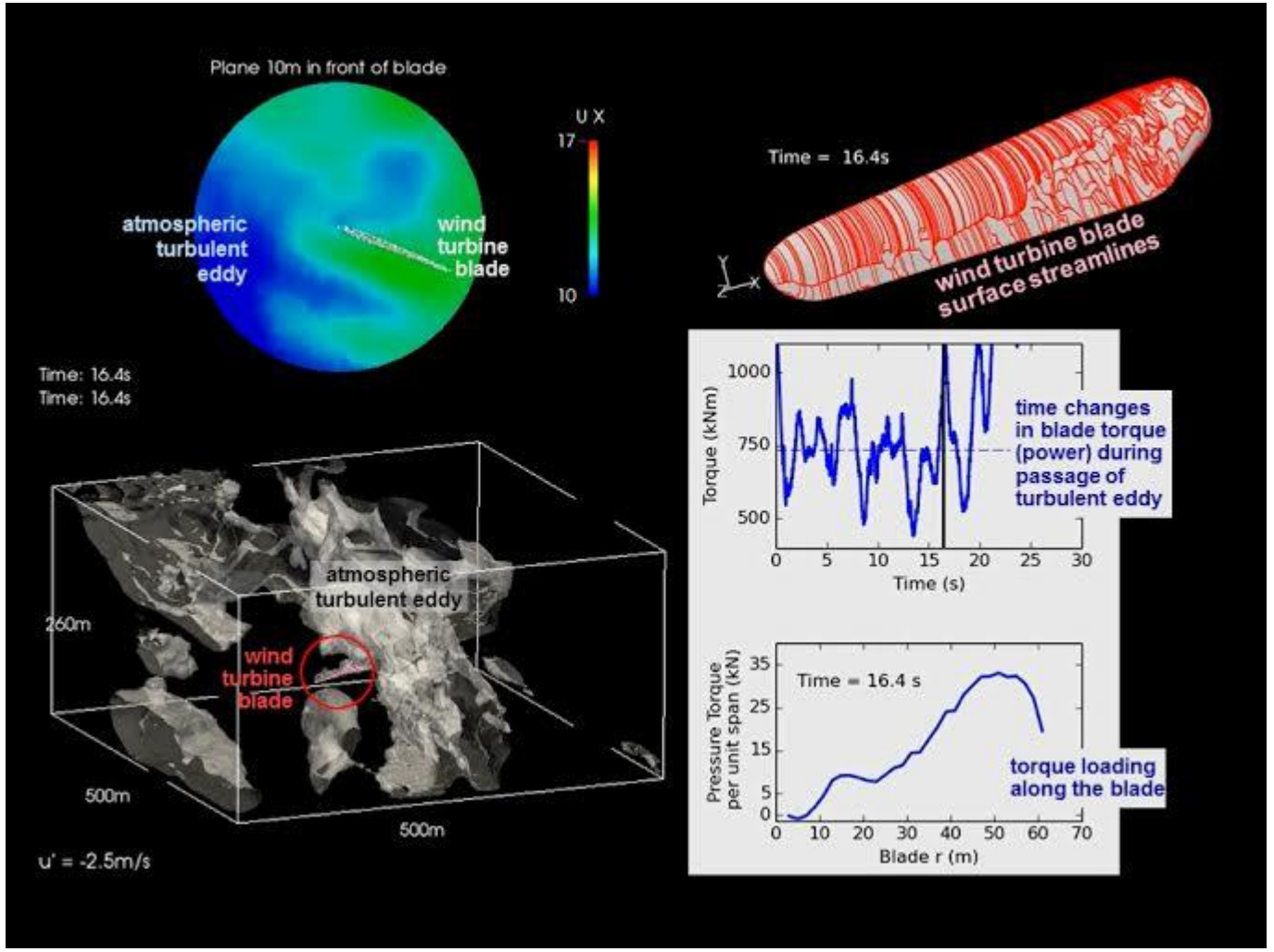


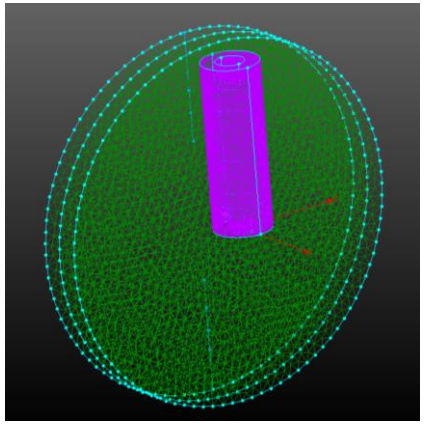


Interpolation to a coarse mesh for volumetric analysis



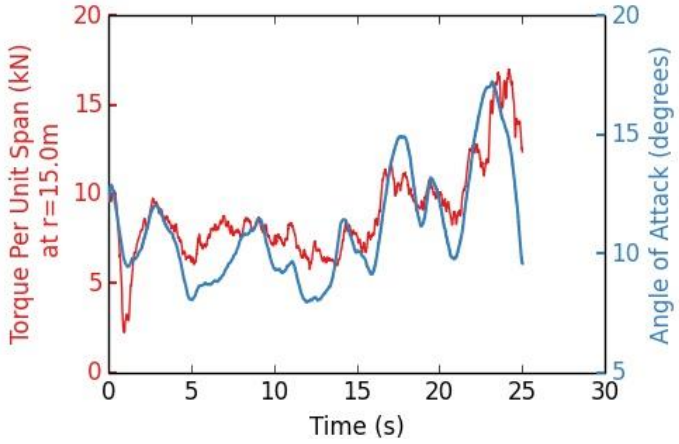
The largest fluctuations on the wind turbine loads are due to ABL structures ~ O(rotor disk).

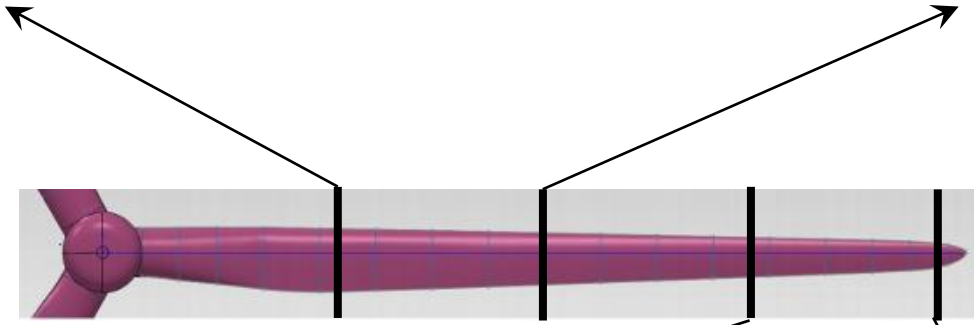


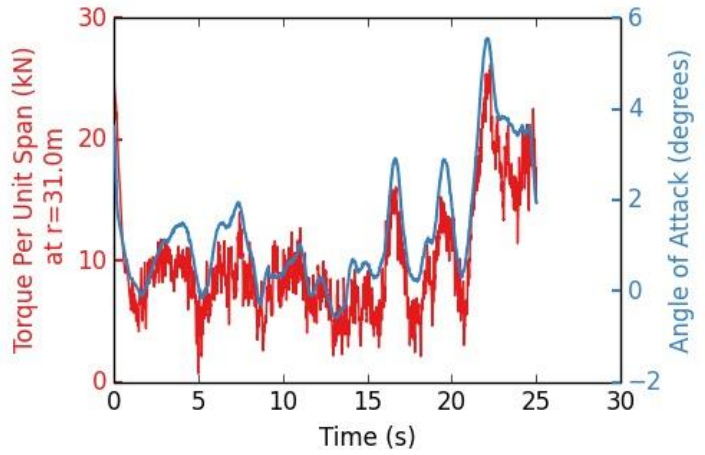


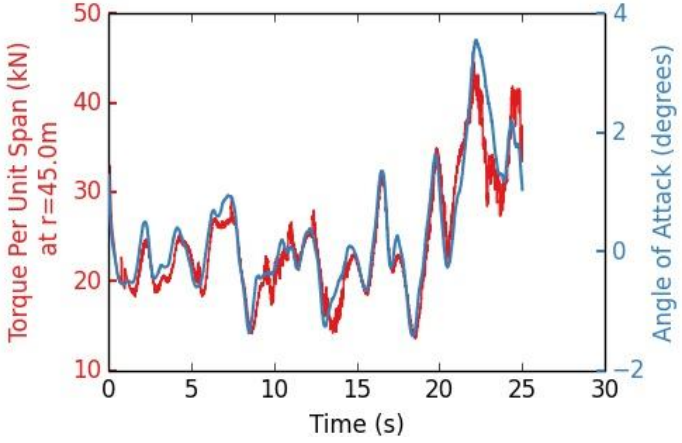
Disk 10m in front of blade

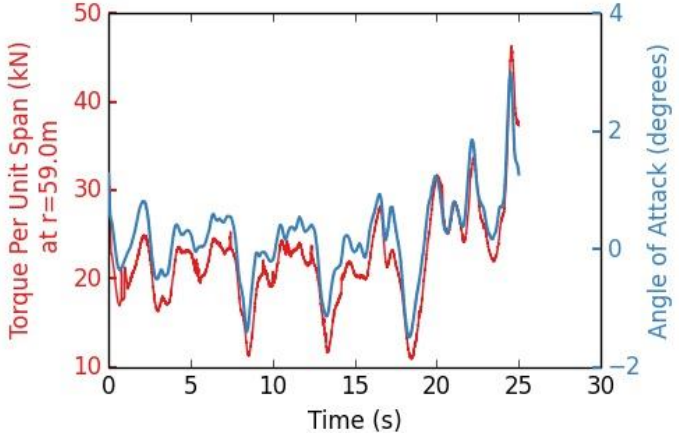
Atmospheric turbulence causes fluctuations in the integrated loads primarily through changes in the angle of attack.





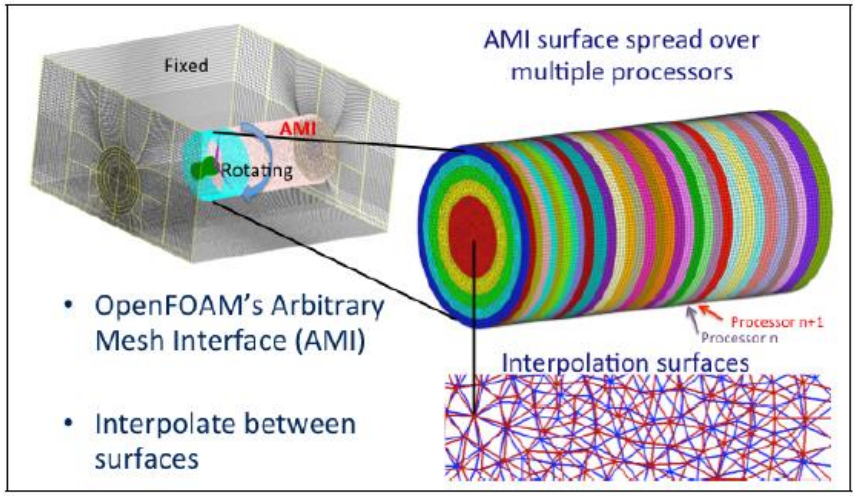






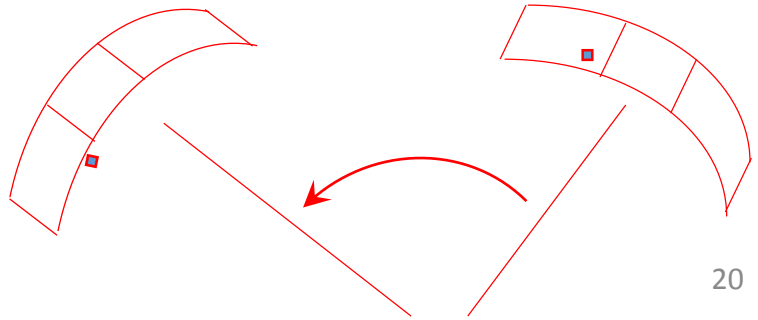
Particular problems with OpenFOAM implementation

✓ Scaling to large number of cores with AMI – Adam Lavely



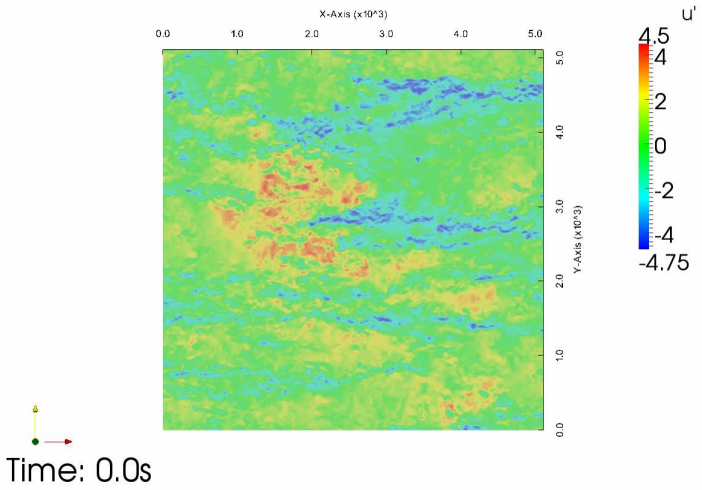
⊙ File I/O at large # cores – Too many files – Working on a HDF5 based solution with Dr. Anirban Jana and Si Liu @ XSEDE

✗ Interpolation near the blade surface – grid sizes - ~ 1 μm



Conclusions

① Energy containing scales in ABL
- ~ NREL 5MW turbine disk
- ~ Multiple rotation time scales



② **Simulation across scales**
- **~ 9 orders of magnitude.**

③ The turbulence structures ~ $O(rotor\ disk)$ cause the largest fluctuations in the integrated loads primarily through changes in the angle of attack.

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- "Kulakowski Travel Award" – Mech. Engg. @ PSU
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  – Dr. Earl Duque
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